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14. ABSTRACT

Modern rockets operate at supercritical pressures with respect to propellants. There is a need to understand mixing and combustion beyond liquid and gas states. Shear coaxial injectors are a common choice for cryogenic liquid rocket engines. Interactions of transverse acoustics with an injector's own modes and mixing need to be understood in terms of combustion instability. There is a need to understand the differences in response to pressure and velocity nodes. There is a need to understand what non-dimensional numbers capture the mixing of typical injectors, and to characterize how geometry affects mixing. In this presentation, relevant physics of shear coaxial jets are explored; highlights from literature review are listed; and experimental set-ups are described.

15. SUBJECT TERMS

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Coaxial Injectors Subjected to External Acoustics

Ivett Leyva

Students (current and past): Sophonias Teshome, Juan Rodriguez, Jeff Graham

Co-advisors: Doug Talley, Ann Karagozian

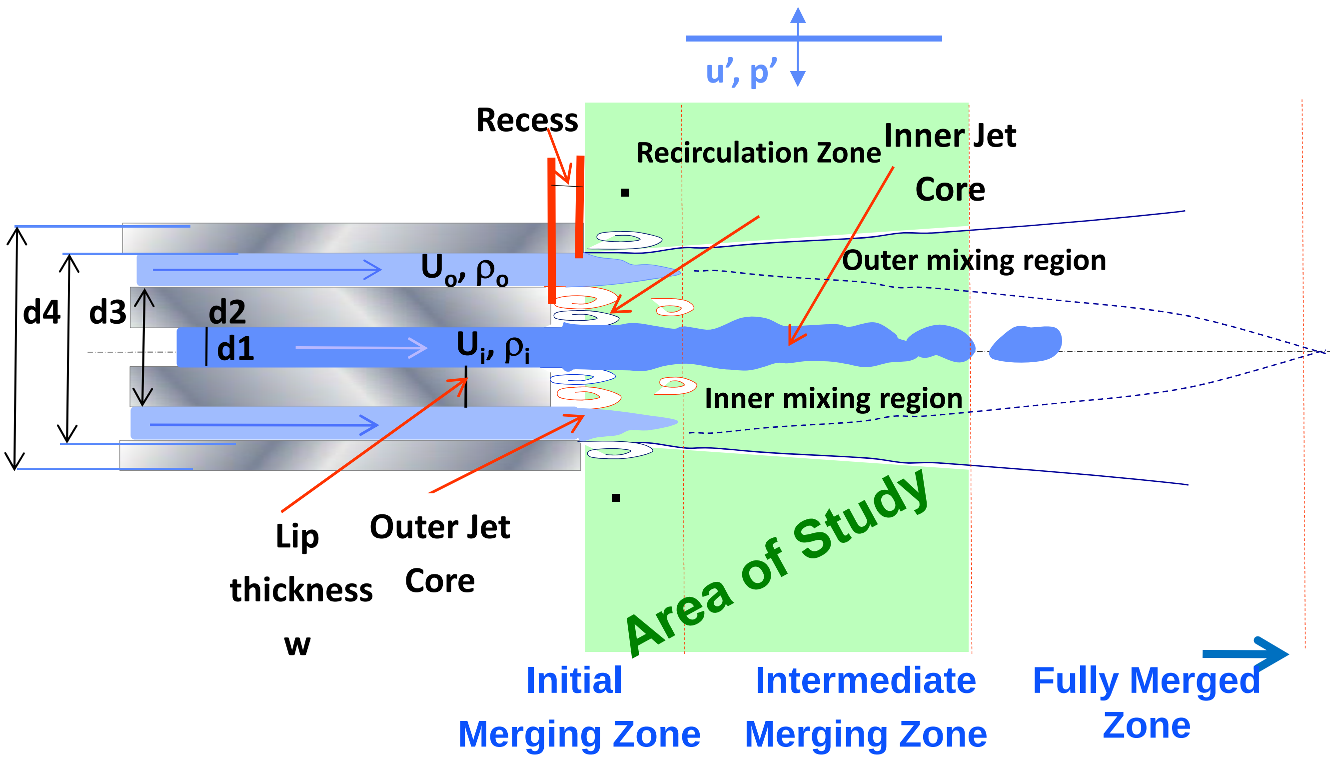
October 20, 2011

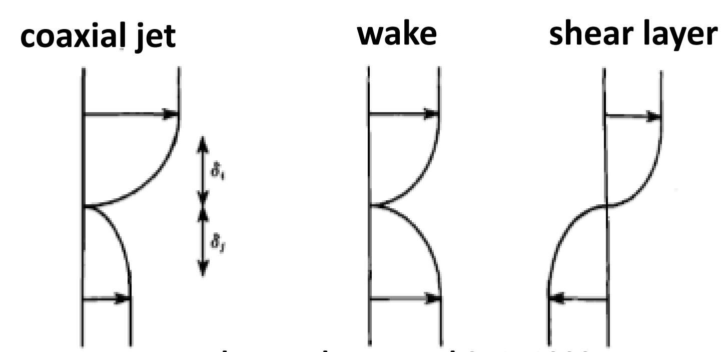
Statement of need

- Modern rockets operate at supercritical pressures with respect to the propellants
    - Need to understand mixing and combustion beyond liquid, gas states
- Shear coaxial injectors are a common choice for cryogenic liquid rocket engines
- Interactions of transverse acoustics with injector's own modes and mixing needs to be understood for combustion instability
    - Need to understand differences in response to pressure and velocity nodes
- Understand what non-dimensional numbers capture the mixing of typical injectors
- Characterize how geometry affects mixing

Relevant physics of shear coaxial jets

1. **Transverse Acoustic mode from chamber/siren**
   - $f=f(c, \text{geometry})$
2. **Acoustic modes for outer and inner jets**
   - $f \sim c/2L$ – 2 speeds of sound up and downstream
3. **Wake resulting from inner post thickness**
   - $St=fw/U_{ch}$
4. **Shear layer instabilities**
   - $St_\theta=f\theta/U_{ch}$
5. **Jet preferred modes**
   - $St=fD_{ij}/U_{ij}$

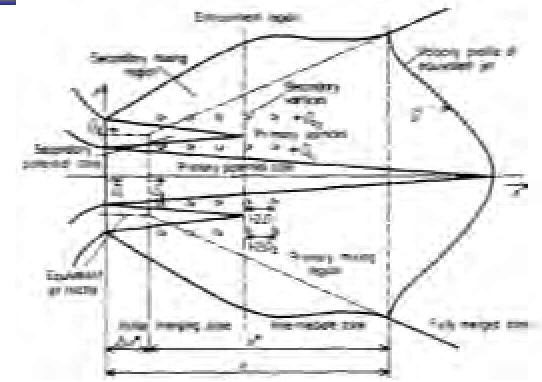




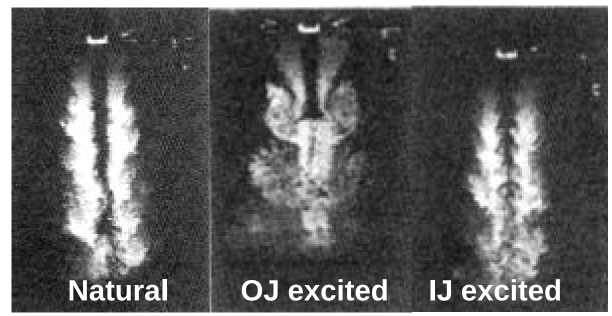
Dahm et al, JFM, Vol 241, 1992

Highlights from literature review (1 of 2)

- **Michalke, 1964**
  - **Linear stability theory for inviscid instability of a hyperbolic tangent velocity profile**
- **Crow and Champagne, 1971**
  - **Single jet preferred mode, St_d=fd/U~0.3**
- **Ko et al,1976-1989**
  - **Some of earliest detailed description of near field mixing for coaxial jets**
- **Boldman et al, 1975**
  - **Experimental and theoretical analysis for mixing of two air streams with different velocities – points out different vortex interactions, St_l~0.2 (U_{ave})**
- **Gutmark and Ho, 1983**
  - **Collects previous results on jet preferred mode, St_d has a range from ~0.24-0.64**
- **Wicker and Eaton, 1994**
  - **Forces air inner and outer jets independently – observes vortex growth**
- **Dahm et al, 1992**
  - **Seminal pictures of different instabilities plus effect of absolute velocity and R**



Kwan and Ko, J. Sound and Vibration, 48 (2), 1976

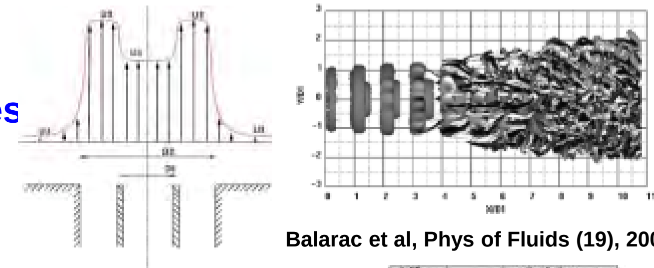


Wicker and Eaton, AIAA J, (32) No.3,1994

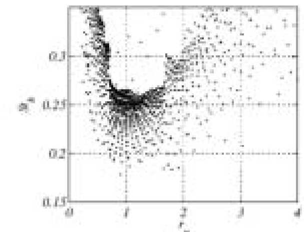
Dahm et al, JFM (241) 1992

Highlights from literature review (2 of 2)

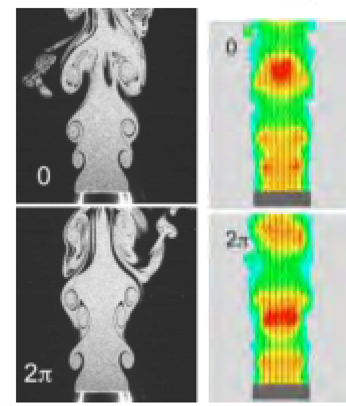
- **Balarac, da Silva, Metais et al (2003, 2007)**
  - DNS analysis of coaxial jets - same density, top-hat profiles
  - Consider two shear layers, study effect of R
  - Consider axisymmetric and azimuthal excitation
- **Buresti, Talamelli, Petagna (1994, 1998)**
  - Air jets, same density, top-hat profile, $St_{do}=fd_o/U_{oj}$~0.3 to 1, function of x/D_i
- **Segalini, Talamelli, et al (2006, 2011)**
  - Air jets, same density, top-hat profile, $St_{b(lip)}=fb(lip)/U_{average}$
- **Birbaud, Ducruix, Durox, Candel (2006-2007)**
  - Single air jets, low Re, laminar, top-hat profile, subjected to acoustic modulation
  - Systematic study of effect of modulation in terms of St_d, St_θ
- **Tshohas, Canino, Heister (2004, 2009)**
  - 2D unsteady CFD for LOX/H2 elements but non-reacting
  - Unforced behavior, found $St_{lip}=fd_{lox}/U_{lox}$~0.10-0.25
- **Richecoeur, Scouflaire, Ducruix, Candel (2006)**
  - Forced transverse acoustic excitation of flames



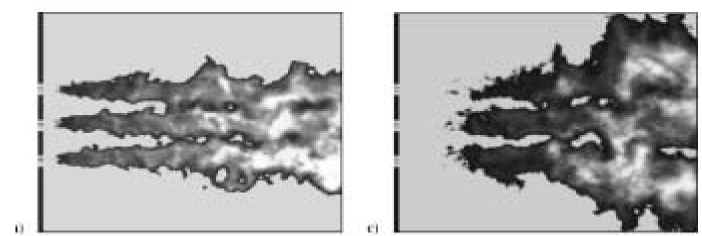
Balarac et al, Phys of Fluids (19), 2007



Segalini et al, Phys of Fluids (23), 2011



Birbaud et al, Phys of Fluids (19), 2007

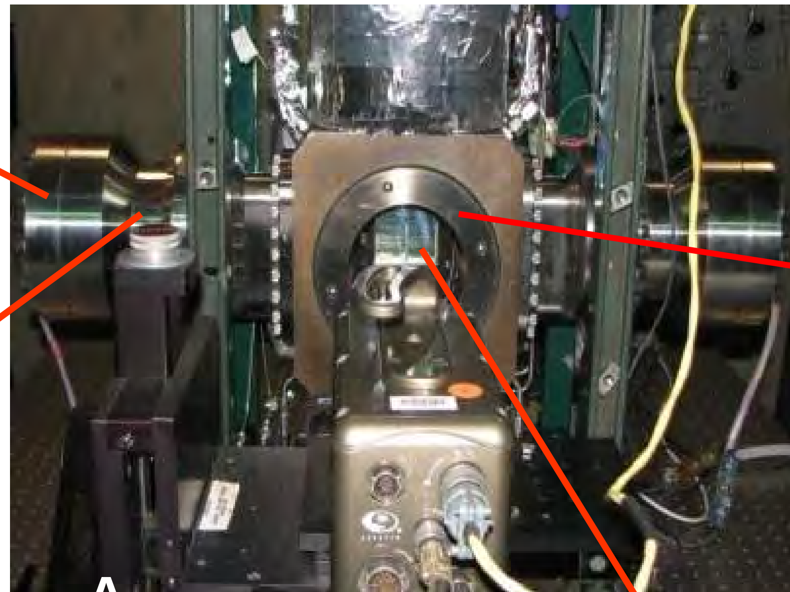


Richecoeur et al, JPP (22) No 4, 2006

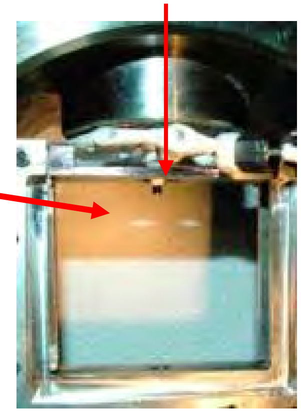
Experimental setup – EC-4

Piezo-Siren

Waveguide

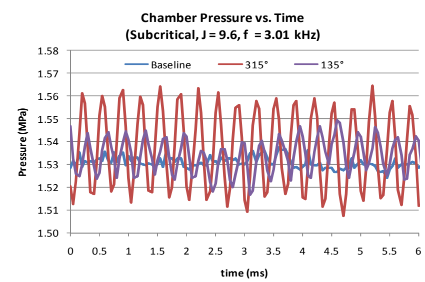


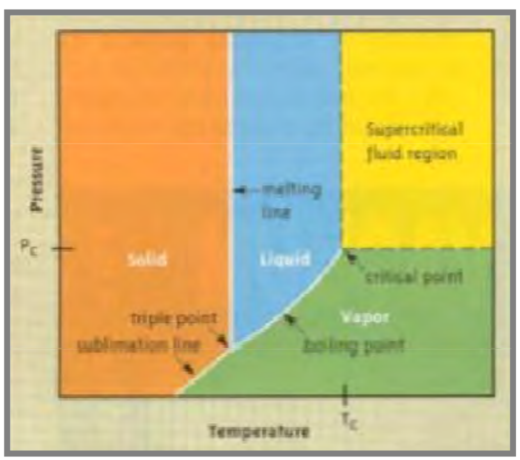
Coaxial Injector



Inner Chamber

f=~3kHz



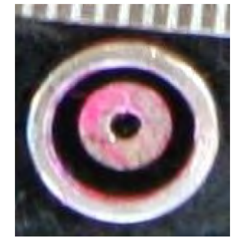


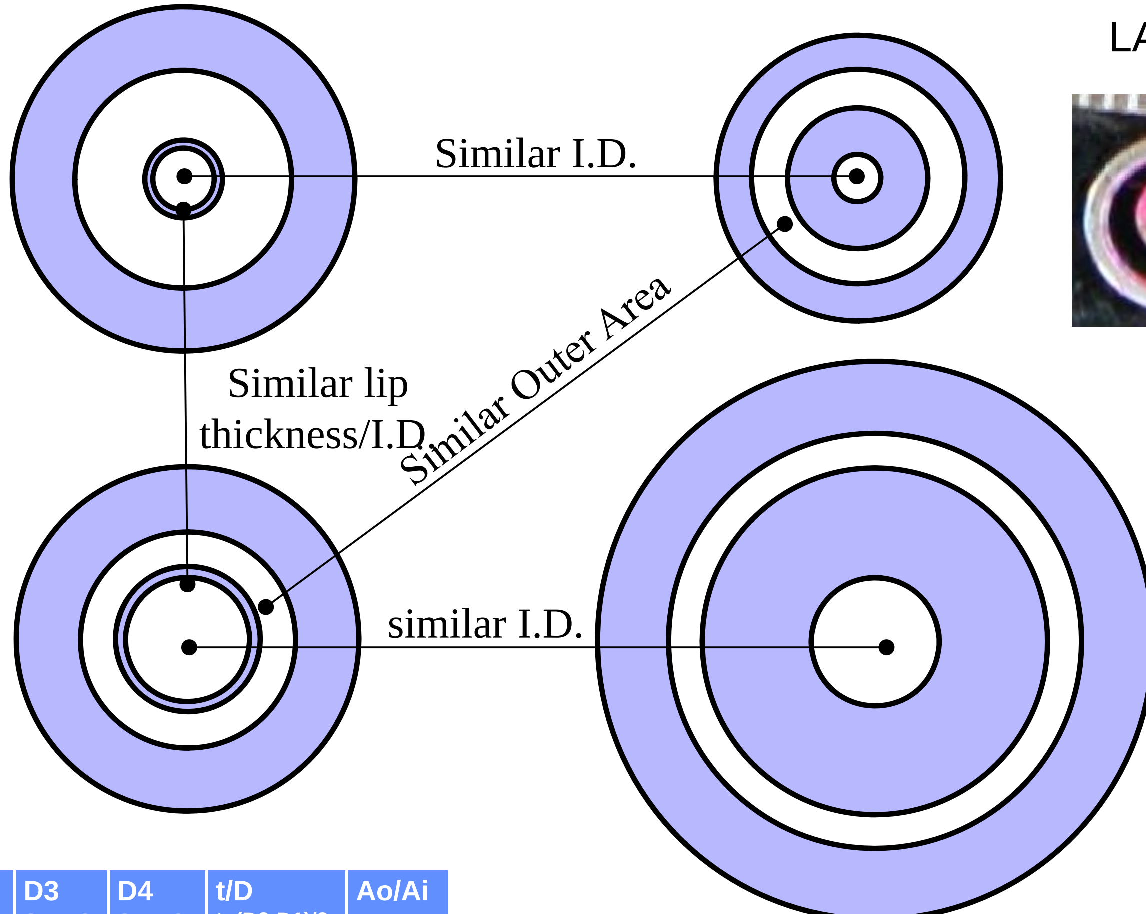
Thermocouple and P transducer

Geometric Rationale

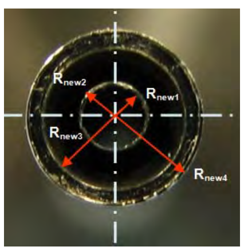
LAR_ThinLip

LAR_ThickLip





SAR_ThinLip



SAR_ThickLip

Two recesses

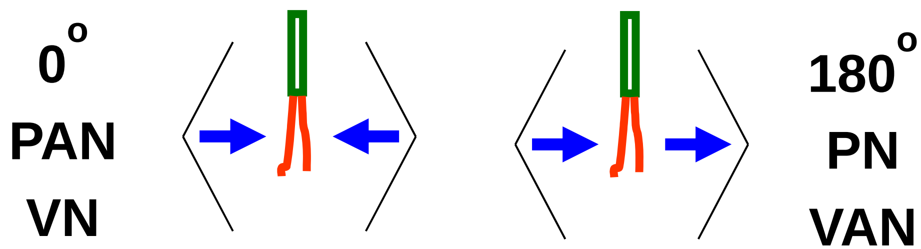
	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	t/D t=(D2-D1)/2	Ao/Ai
LAR_thickLip	0.51	1.59	2.42	3.18	1.05	12.9
SAR_thinLip	1.40	1.65	2.44	3.94	0.09	1.6
SAR_thickLip	1.47	3.96	4.70	6.35	0.84	2.9
LAR_thinLip	0.70	0.89	2.44	3.94	0.13	10.6

SAR, LAR -> Small, Large Area Ratio

ThickLip, ThinLip -> Post lip thickness

Other parameters varied

- **Momentum flux ratio** $J=\rho_o u_o^2/\rho_i u_i^2$
- **Velocity ratio** $R=u_o/u_i$
- **Thermodynamic state**
  - **Subcritical to supercritical**
- **Acoustics**
  - **Acoustics off**
  - **Acoustics on (with and without mode matching)**
    - **Phase of the acoustics:**
      - **0 degrees: Pressure Anti Node (PAN) (velocity node (VN))**
      - **180 degrees: Pressure node (PN) (velocity antinode (VAN))**

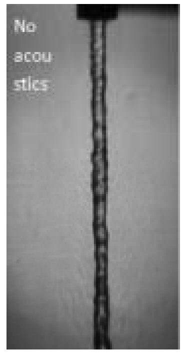


Chronological progression (only coaxial results are summarized in what follows)

- **Single jets, no coaxial flow**
  - Davis et. al. (Ph.D. thesis) – single jets, no coaxial flow
    - Not briefed today
- **Coaxial jets**
  - Leyva et.al. – LAR_thick
  - Rodriguez et. al. (Ph.D. thesis) – LAR_thick, SAR_thin
  - Graham et. al. – SAR_thin, two recesses
  - Teshome et. al. (Ph.D. thesis, expected Mar 2012) – complete all four geometries
    - Also complete modal analysis of earlier geometries
- **Future: Combusting coaxial jets**
  - Wegener et. al. (Ph.D. thesis) (in process)
  - Article 219 facility funds

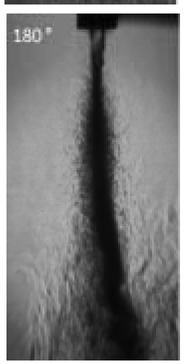
Image interpretation key

Baseline:
Acoustics
off



0^o
Acoustics on
PAN, VN
"Pressure coupled"

180^o
PN, VAN
Largest difference
expected from 0^o
"Velocity coupled"



pressure = fixed

J $(\rho_o u_o^2/\rho_i u_i^2)$ = fixed

PN – pressure node - Min
PAN – pressure antinode - Max
VN – velocity node
VAN – velocity antinode

Sub-Critical Pressure: Two Geometries

LAR_thickLip | **LAR_thinLip**

Baseline

PAN

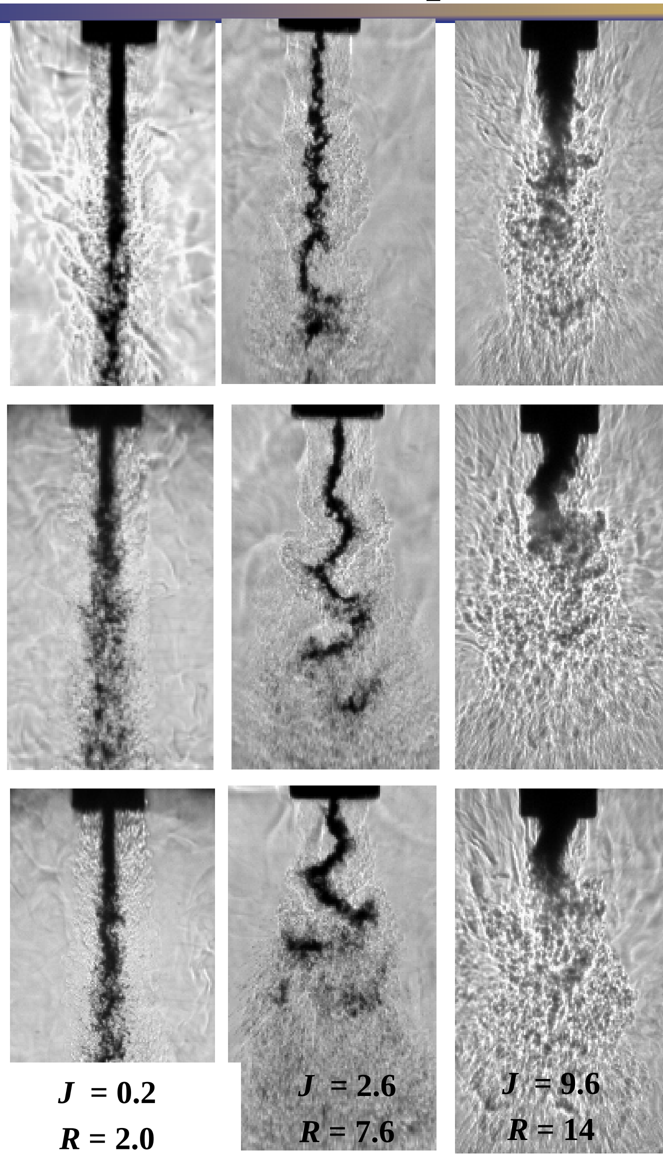
P
antinode

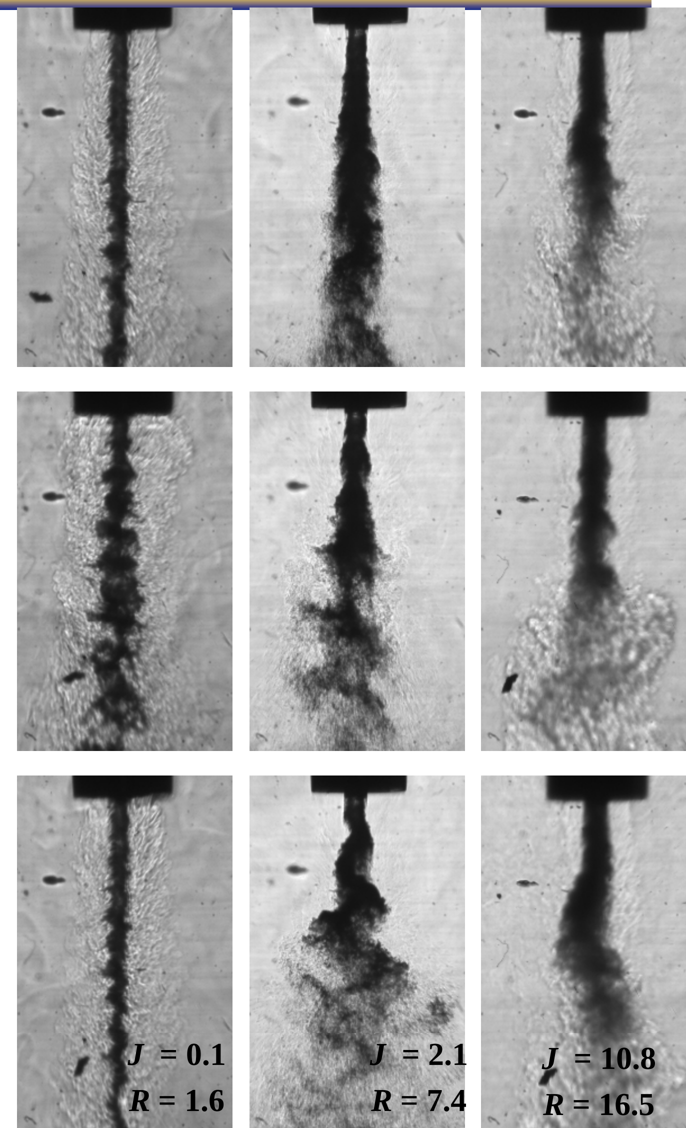
PN

P node

$J = \rho_o u_o^2 / \rho_i u_i^2$

$R = u_o / u_i$





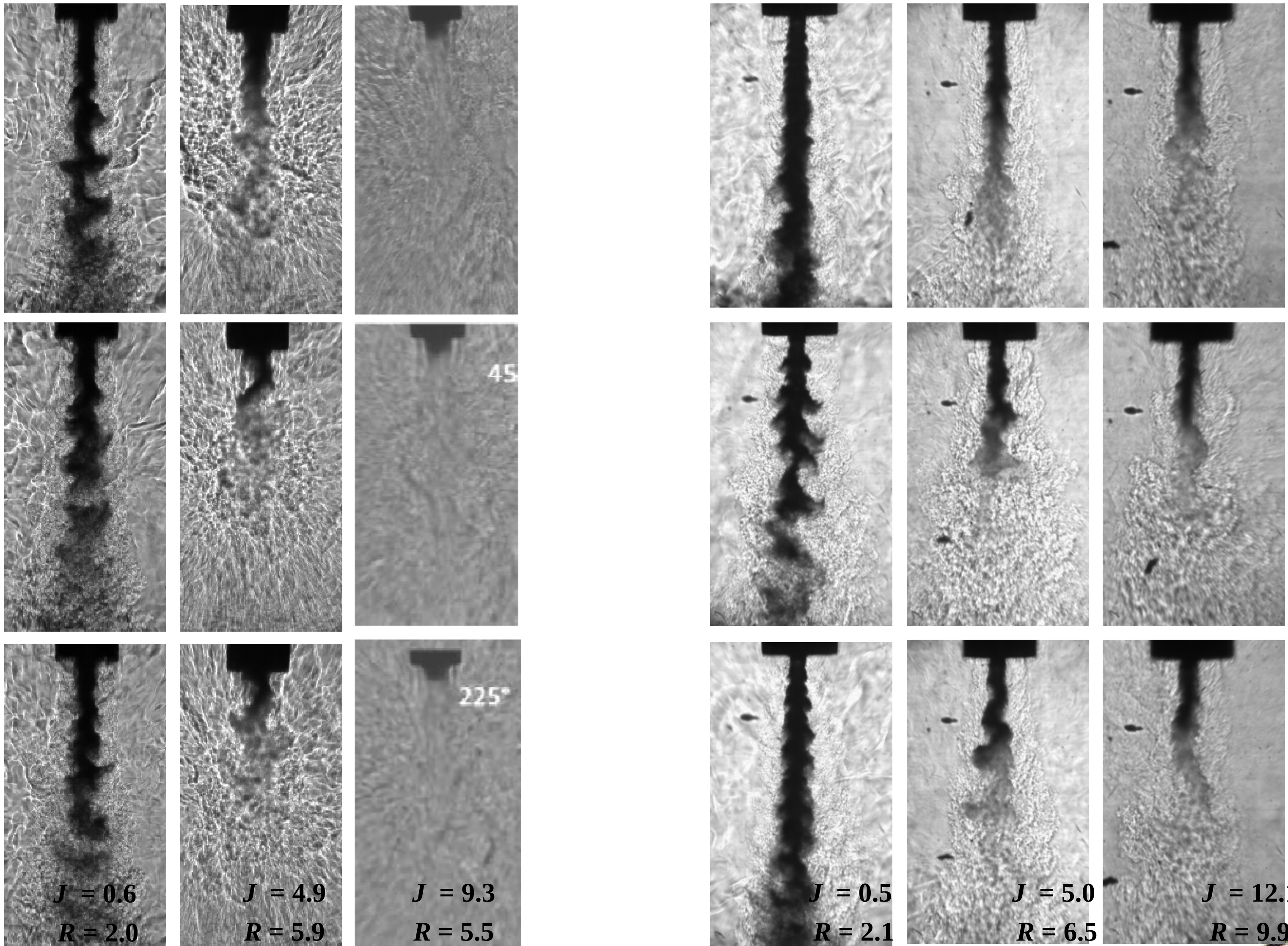
Near-Critical Pressure: Two geometries

LAR_thickLip **LAR_thinLip**

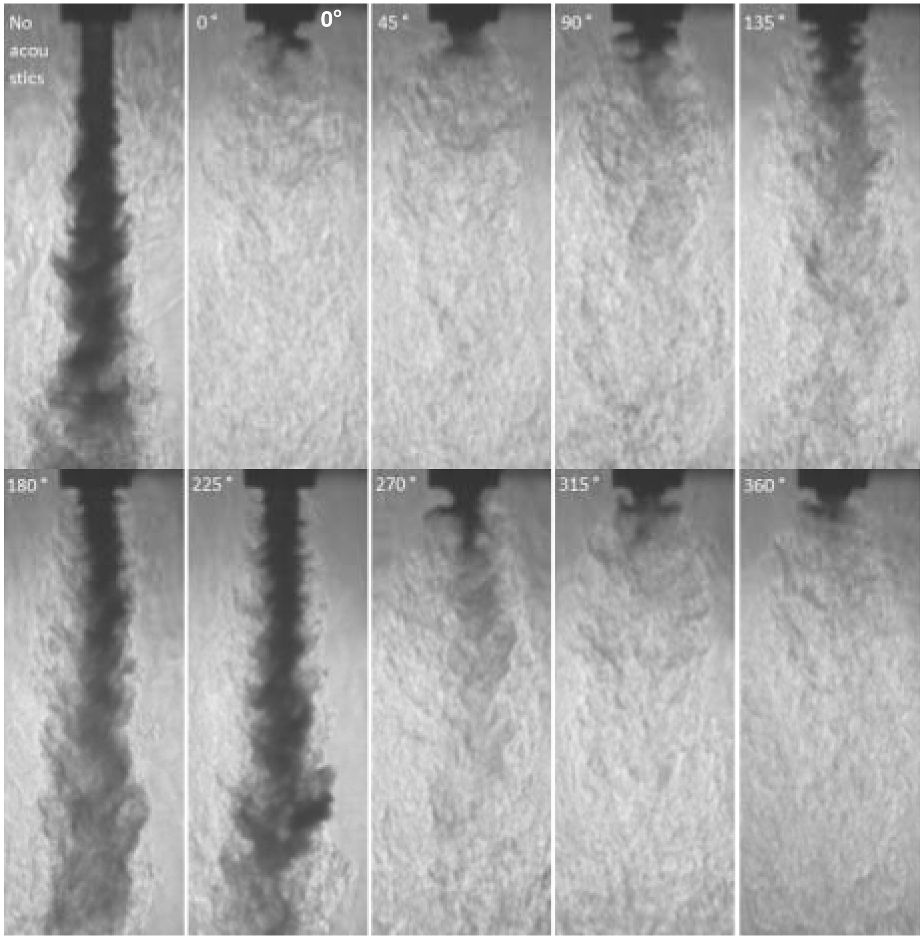
Baseline

PAN

PN



SAR_thinLip



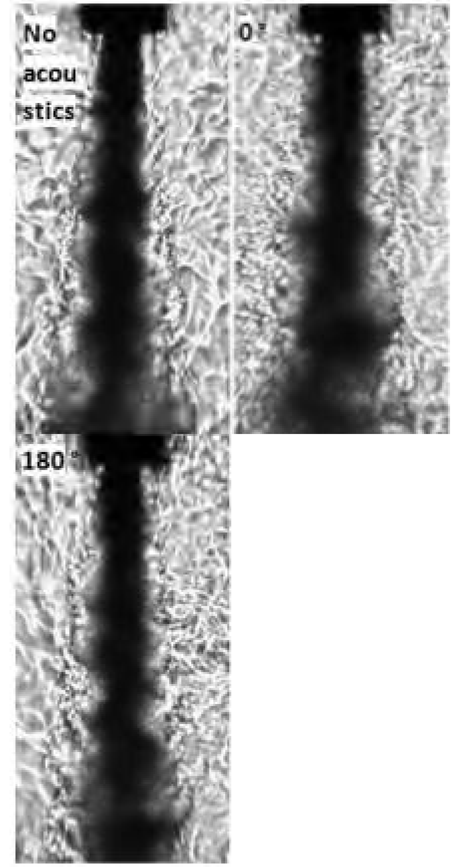
Pr=1.05, J=1.7, p´/p=0.32%

Coupled to Outer Jet Acoustic Mode

- **Nearcritical conditions**
  - **No jet bending observed**
  - **large vortical structures generated when coupled to injector mode**
  - **Reduction of dark core can be as large as 90%**
  - **More clear response of jet to pressure antinode**
- **Subcritical conditions**
  - **Same mode – vortical structures**
  - **Not as dramatic reduction as with nearcritical cases**

Pr=1.05, J=0.5, R=2

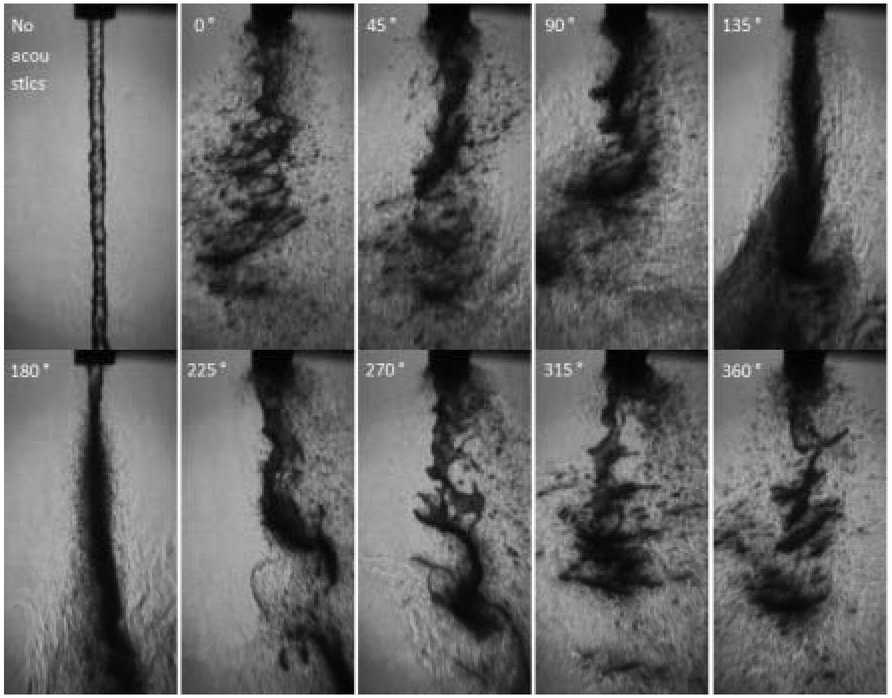
Pr=1.05, J=0.5, R=1.3



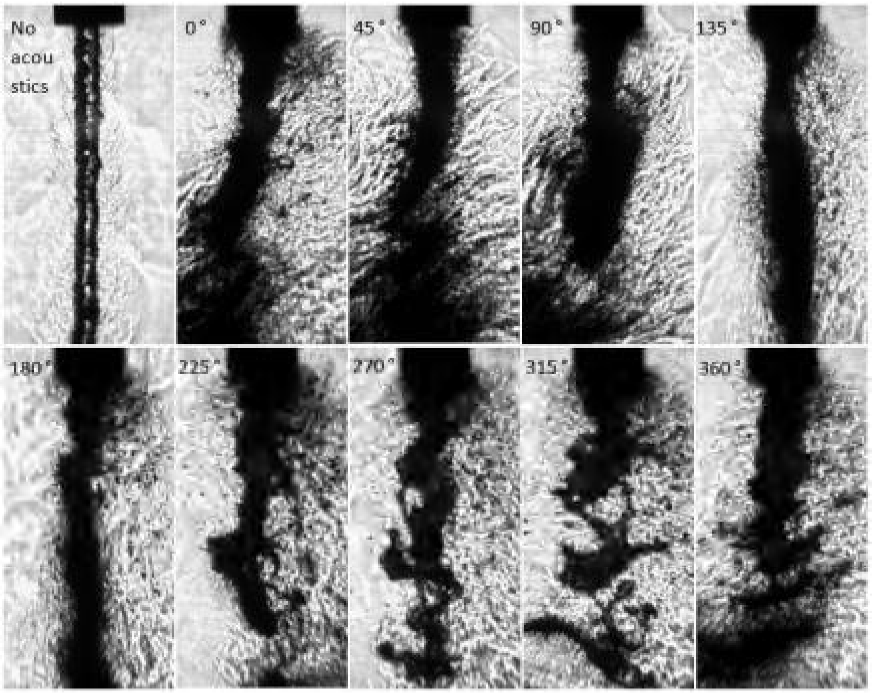
Pr=1.05, J=2.2, p´/p=0.25%

Non Coupled

Effect of Recess: SAR_ThinLip; Pr=0.45, J~0.09



Flush inner post, J=0.09, p´/p=0.45%

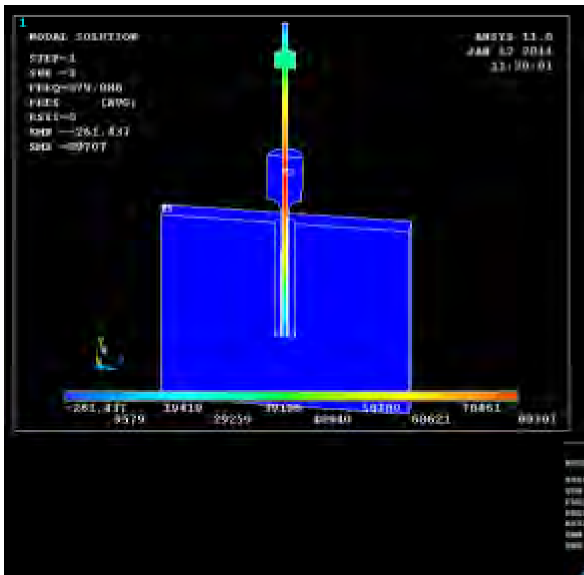


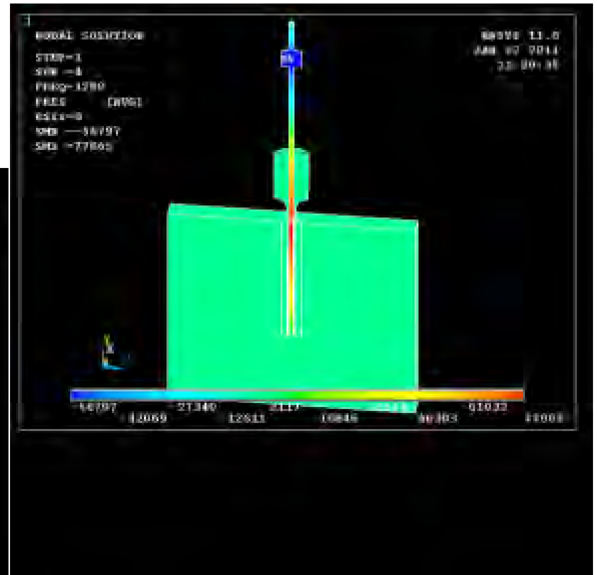
Recessed inner post, J=0.089, p´/p=0.60%

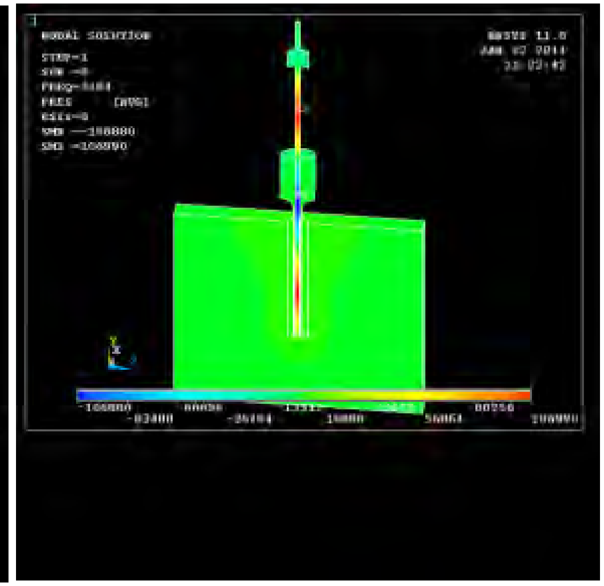
Qualitatively similar at very low J values

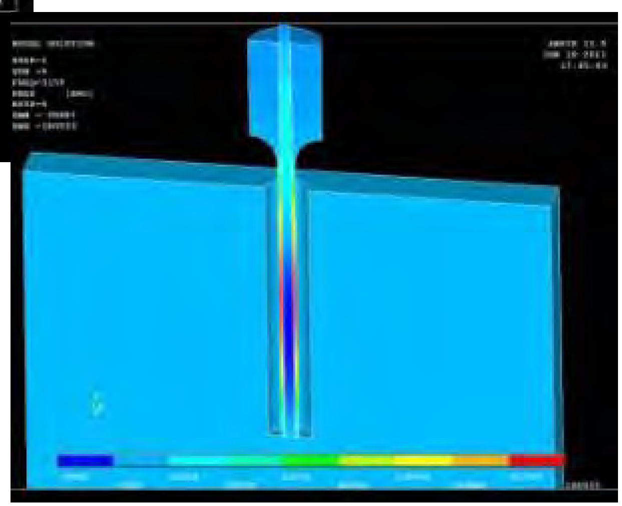
Acoustic Analysis for Injectors

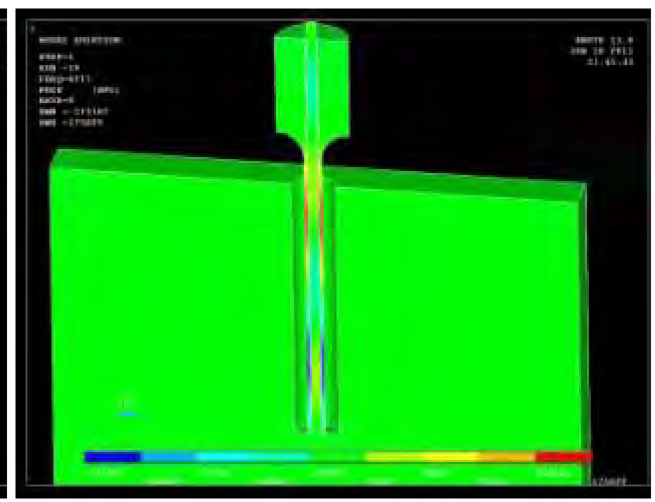
In collaboration with Jeff Muss and Rory Davis, Sierra Engineering





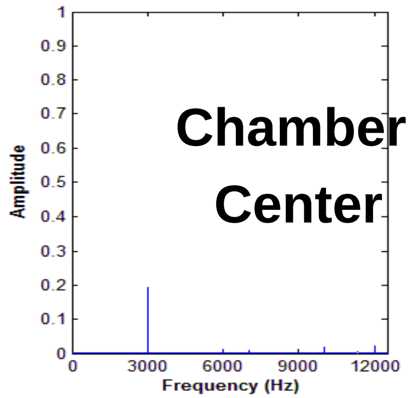


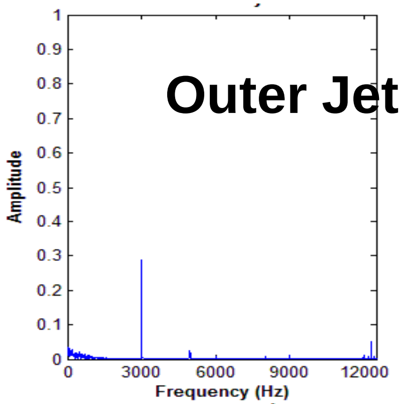


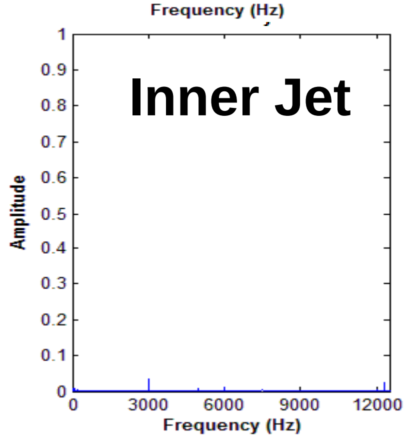


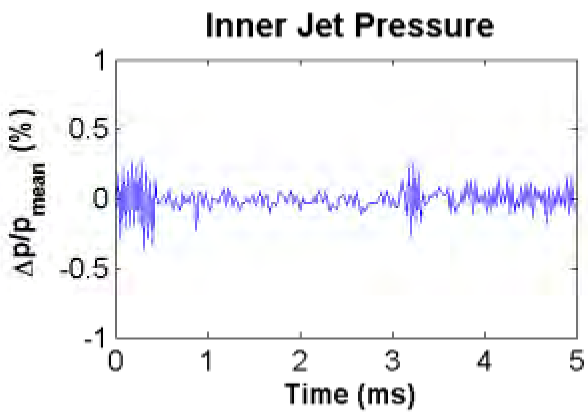
Have more accurately computed the acoustic modes for the inner and outer jets for constant and linearly varying temperatures for subcritical and supercritical pressures

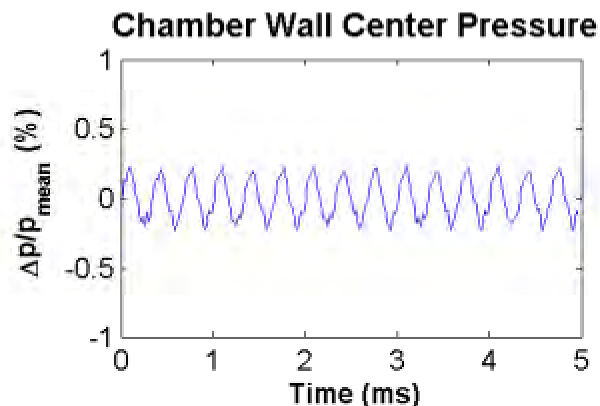
New analysis: synchronized p’ and images taken with microscopic lens







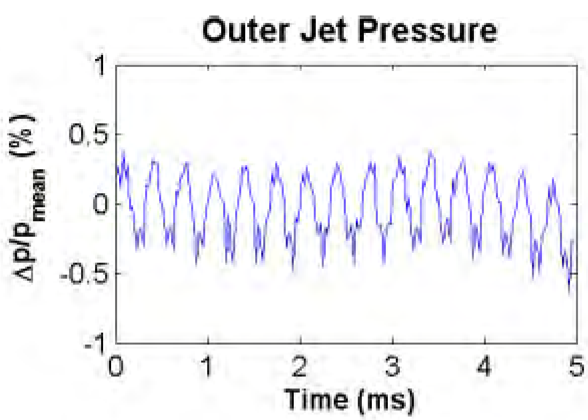


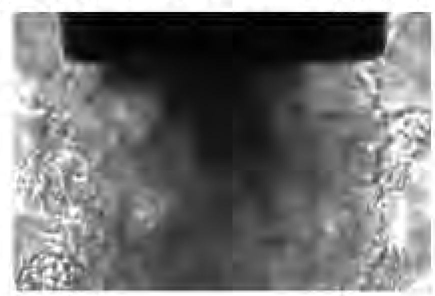


Inner Injector Recessed 0.5 D_i

Pr = 1.03, J = 5.1, VR = 5.9

Forcing Condition: 3000 Hz, Maximum Δp



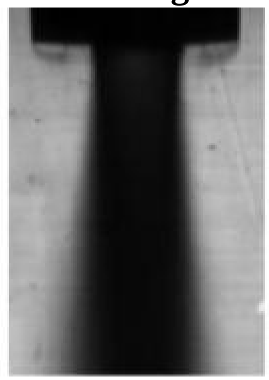


Uo=6. 25 m/s, Ui=1.06 m/s, To=165K , Ti=118 K

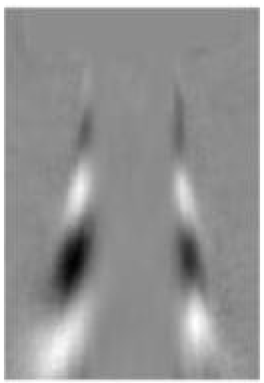
Case I: Baseline Flow

Snapshot

Average



Mode l



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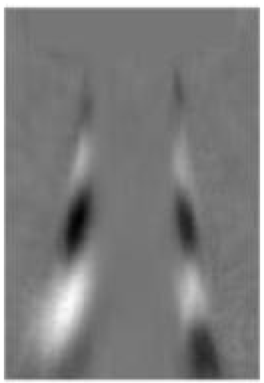
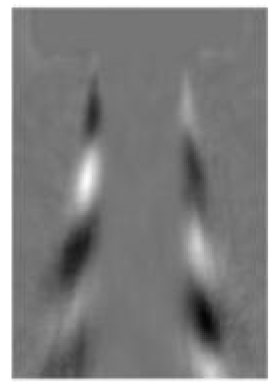


Mode 3

Mode 4

Mode 5



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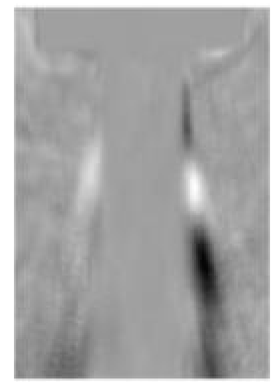
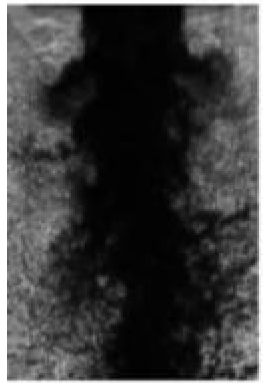


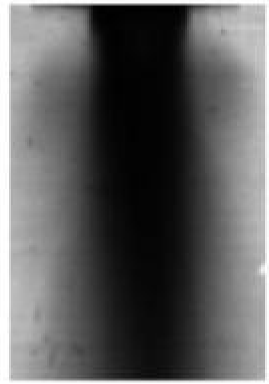
Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J
I	0.44	1.19	0.84	5.8	2.0

Case I: Acoustically Forced Flow

Snapshot



Average



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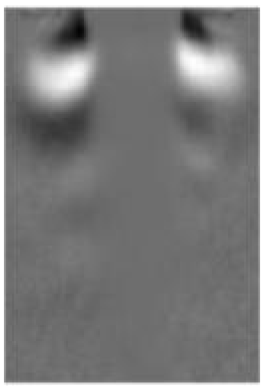

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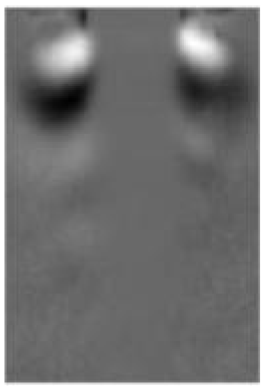

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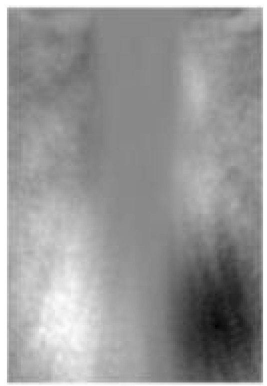
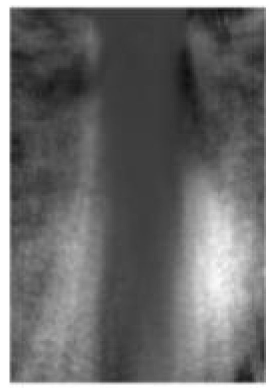


Mode 4



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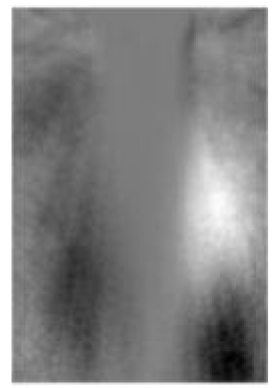
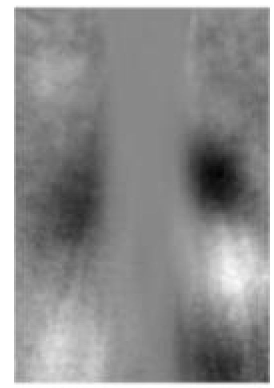


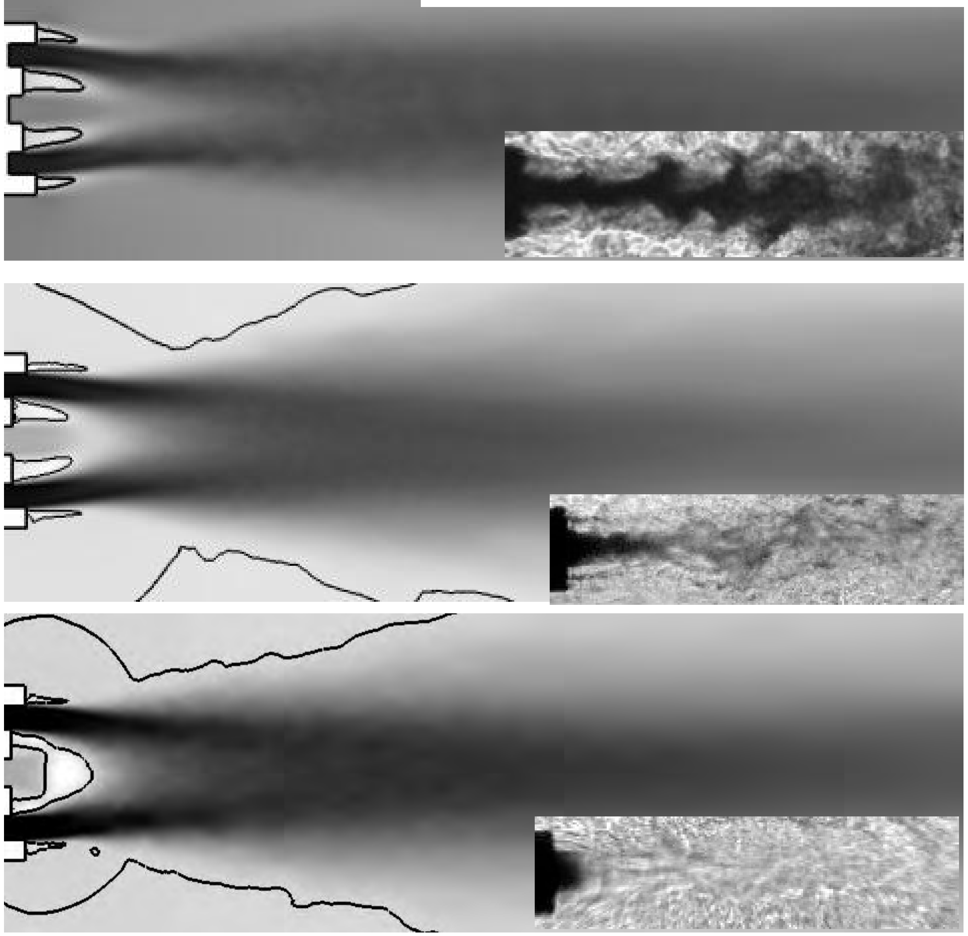
Mode 6



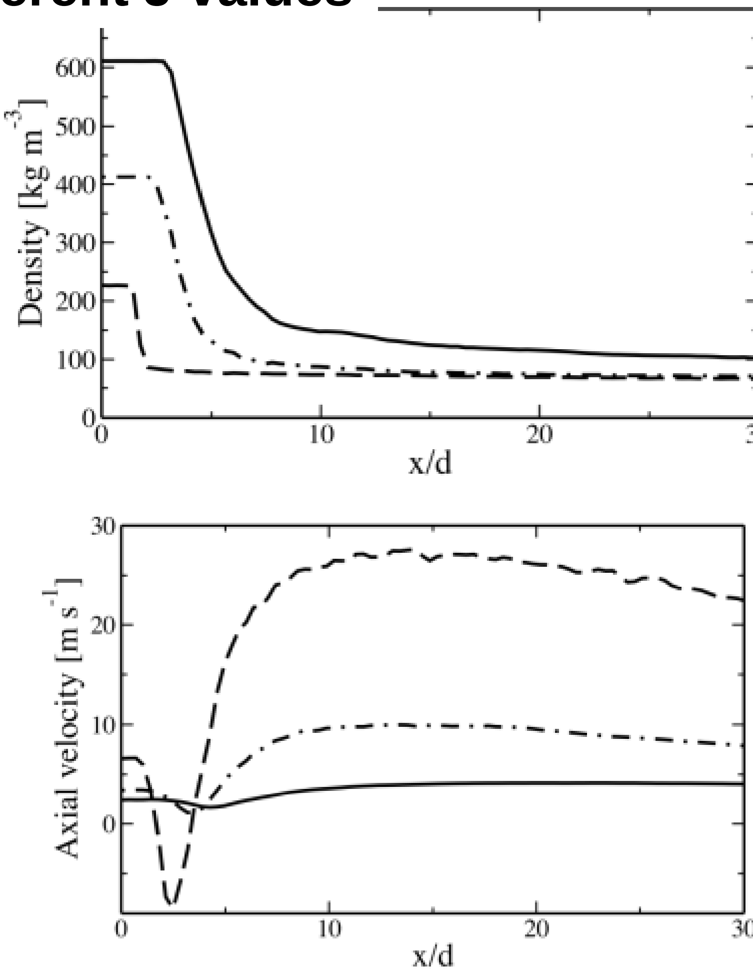
Case	P_R	$T_{R,OJ}$	$T_{R,IJ}$	R	J	f (kHz)
I	0.44	1.19	0.84	5.8	2.0	2.96

Collaboration with ECP: Thomas Schmitt, Juan Rodriguez (AFRL post-doc), Sebastien Candel, Ivett Leyva

Velocity Fields for Different J values



Longitudinal slice of axial velocity. White: minimum; black: maximum. Dark line indicates iso-contour of zero axial velocity. Top: J = 1.1; middle: J = 3.0; bottom: J = 9.3.



Top: centerline profile of density; bottom: centerline profile of velocity. Dark line: J = 1.1; dash point line: J = 3.0; dashed line: J = 9.3.

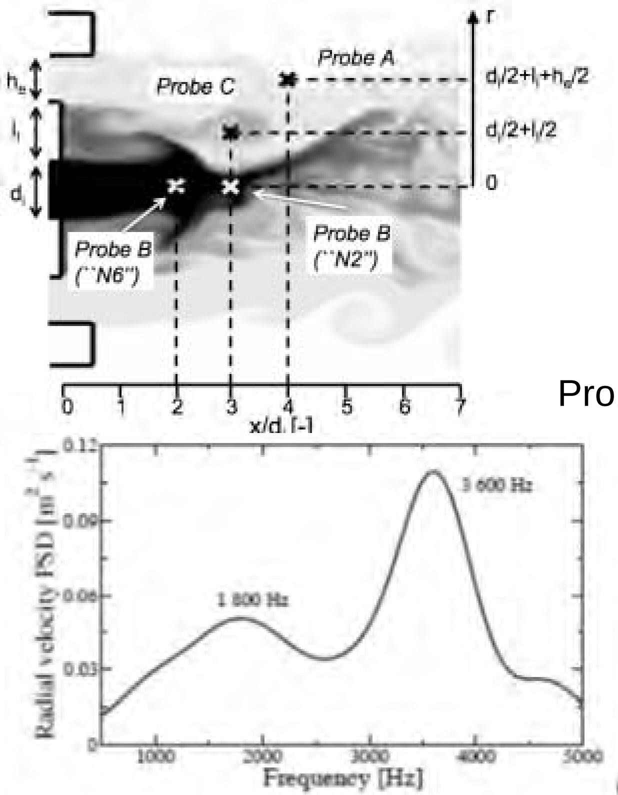
Fundamental frequencies for baseline conditions

Case "N6"
(J=3.05) Density distribution (white: 60 kg/m³; black: 410 kg /m³; logarithmic scale).

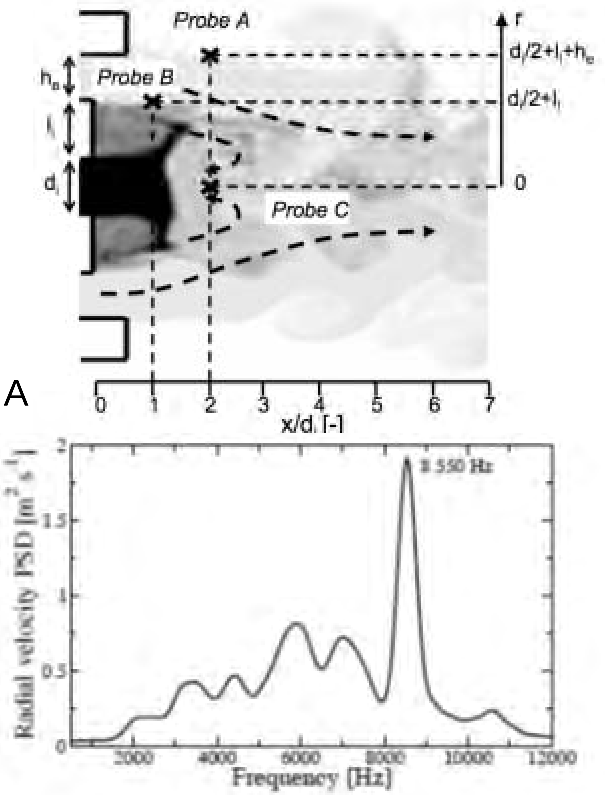
OUTER JET

J=1.05

R=2.48



Probe A



Case "N8"
(J = 9.3) Density distribution (white: 60 kg/m³; black: maximum ; logarithmic scale).

OUTER JET

J=3.05

R=4.18

Case	$St^e = h_e f/U_{oj}$ (probe A)	$St^i = d_i f/U_{ij}$ (probe B)	$St^l = l_i f/U_{oj}$ (probe C)
N2	0.25	0.34	0.15
N6	0.25	0.26	0.14

Found relevant St numbers for our configurations

Conclusions

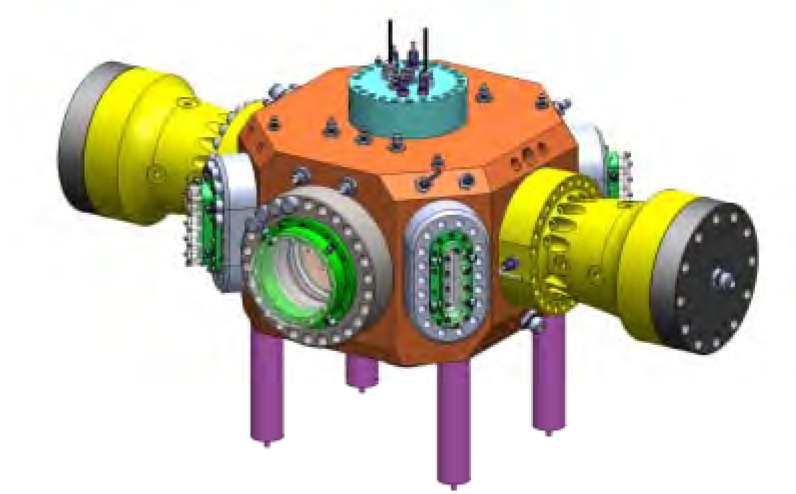
- **For LARthickLip**
  - Found bending mode with largest effect at velocity antinodes
  - The reduction on the dark core length was greatest for a medium J range
  - For near critical pressures, the collaboration with ECP determined relevant St for our injector configuration and was able to capture qualitative behavior of natural and excited jets
- **For SARthinLip**
  - Did not see bending mode for conditions studied
  - Saw vortex roll-up and puffing occurring over entire J range (0.09-21) tested – most predominantly at pressure nodes and most likely associated with acoustic mode of outer jet
  - Vortex roll up and puffing is independent of injector recess configuration
- **For LARthinLip**
  - Sees both bending and vortex roll-up modes depending on the acoustic frequency
- **Synchronized measurements for p' and jet images - correlate structures observed to p' amplitudes**
- **Initial POD analysis recovers features seen in movies – next will be to compute convective velocities of structures observed**

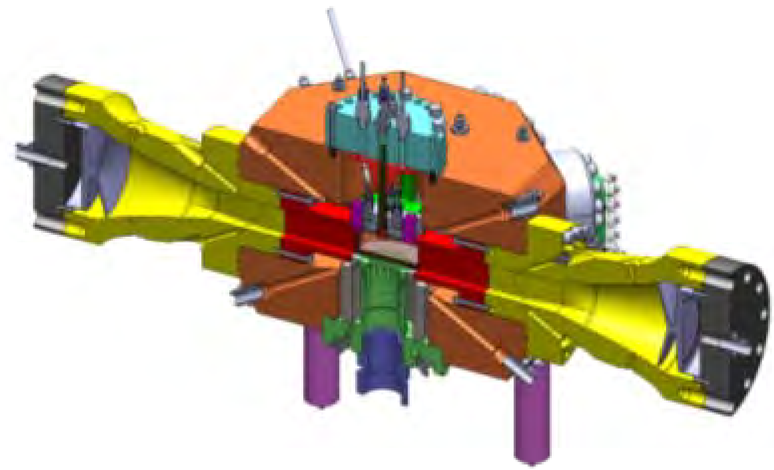
AFOSR/NASA Combustion Stability Workshop

- The single largest unknown in combustion instability is the "combustion response" (how combustion responds to acoustic waves)
- Within the combustion response, flame holding in the near injector field is a key mechanism
- AFRL – Edwards was tasked to develop an experiment and to lead a joint experimental / modeling team to study coupled flame holding mechanisms.
  - *LEVERAGE EXPERIENCE GAINED WITH COLD FLOW EXPERIMENTS*
- GA Tech was selected to lead an effort on a closed-loop study.

EC-4H – Combustion Instability Lab

- Concentrate on near injector field
- Measure p’ and q’ simultaneously to evaluate the Rayleigh criteria for combustion instability
- Start with shear coaxial jets – cold flow heritage
- Lab designed for 2000 psi – about double the pressure from other labs in the world
- Start with current design for acoustic drivers pressure nodes and antinodes





BACKUP

Image interpretation key

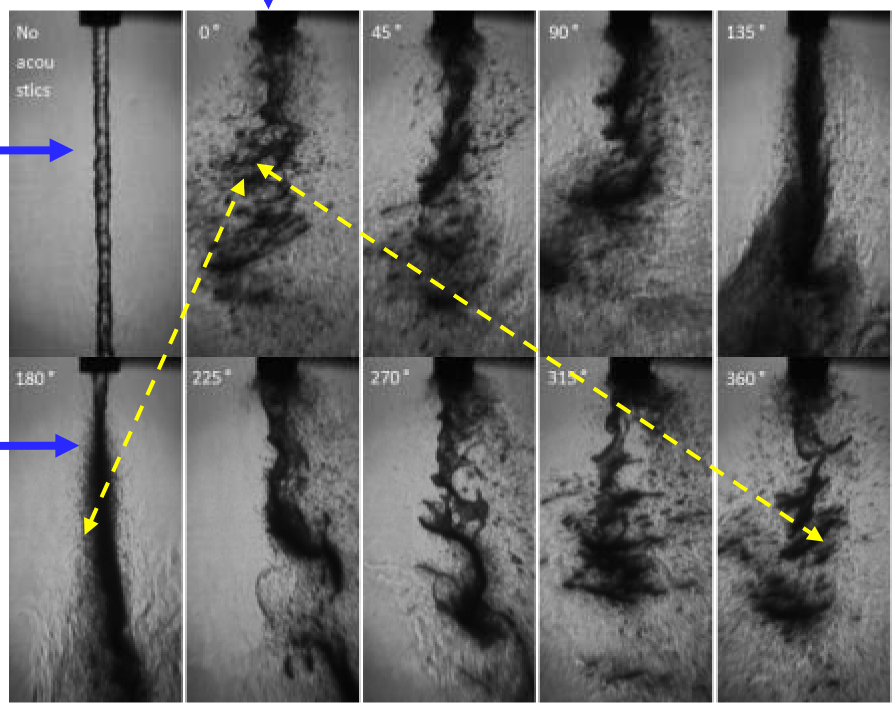
pressure = fixed

J $(\rho_o u_o^2/\rho_i u_i^2)$ = fixed

Acoustics on
0^o
PAN, VN
"Pressure coupled"

Subsequent images:
acoustics on;
Phase increases by 45^o

Baseline:
Acoustics
off

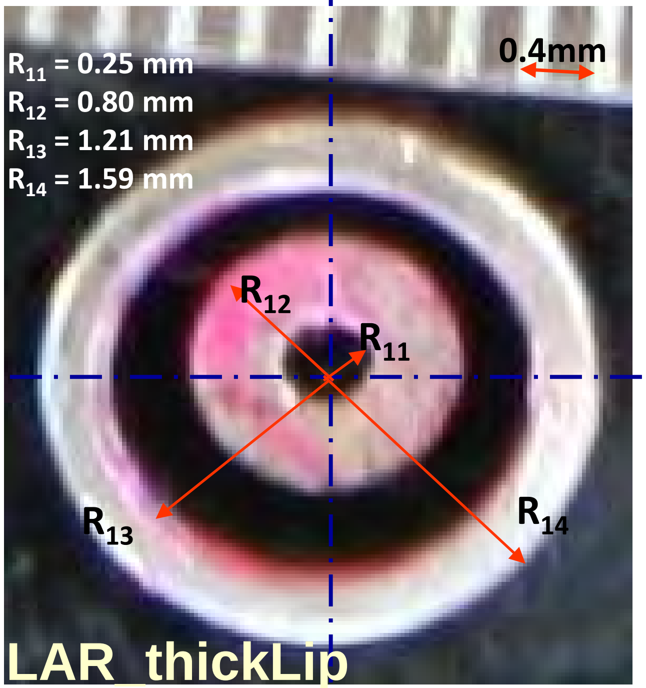


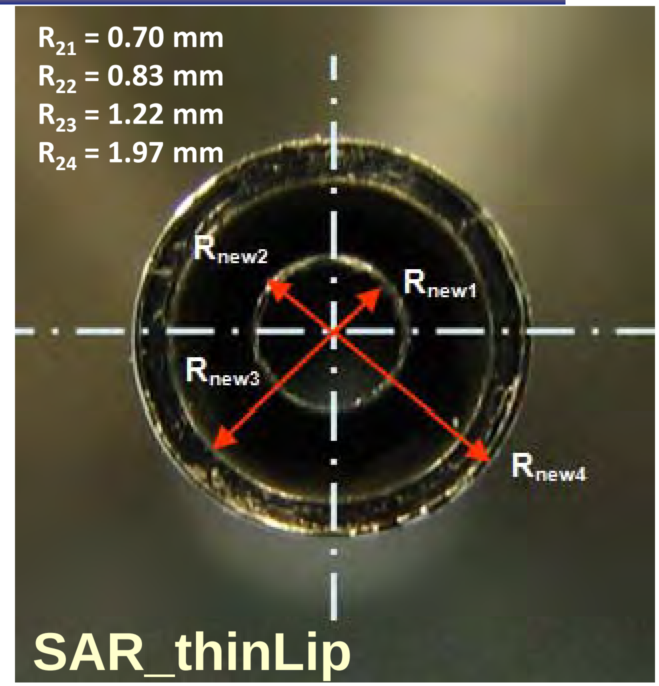
PN – pressure node - Min
PAN – pressure antinode - Max
VN – velocity node
VAN – velocity antinode

180^o
PN, VAN
Largest difference
expected from 0^o
"Velocity coupled"

360^o
should look
similar to 0^o

Geometries for present study





LAR=LargeAreaRatio
SAR=SmallAreaRatio

	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)	t/D t=(D2-D1)/2	Ao/Ai
LAR_thickLip	0.51	1.59	2.42	3.18	1.05	12.9
SAR_thinLip	1.40	1.65	2.44	3.94	0.09	1.6
SAR_thickLip	1.47	3.96	4.70	6.35	0.84	2.9
LAR_thinLip	0.69	0.89	2.44	3.94	0.15	11.0

Relevant variables for cold-flow studies

Geometry	Acoustics	Recess	Phase	VR	J	Coupling
Single Jet	On/Off	N/A	v' max	N/A		No
LAR_thickLip (injector 1)	Off P' max U'max	1/2D1	2-phase P<Pc P>Pc T>Tc T<Tc	0.1-20 0.1-20		No
SAR_thinLip (injector 2)		1/2D1 D1 0				Yes& No
SAR_thickLip (injector 3)		0				
LAR_thinLip (injector 4)		0				